FAILURE PREDICTION IN COMPOSITE PLATES WITH IMPACT-INDUCED DAMAGE

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ABSTRACT

Damage prognosis is an estimate of a system's remaining useful life [1], a necessary part of which includes the use of reliability methods to predict a systems probability of failure for a given loading environment. Damage prognosis of composite structures has the potential to benefit both private and military industries by justifying cost-effective dynamic maintenance schedules. This study attempted to apply a reliability-based model to predict failure in composite plates subject to projectile impact damage. Composite plates were experimentally characterized before and after the introduction of projectile impact damage. A finite element model was developed to direct the application of impact damage, and to demonstrate the feasibility of numerically simulating damage in composite structures. Failure indicators of composite plates were extracted, and a predictive failure model was examined, but results showed that unit-to-unit variability overwhelmed any trends in damage accumulation that were observed.

NOMENCLATURE

H_{pq}	Frequency response function formed by the ratio of the output at 'p' and the input at 'q'	$(\ )_{und}$	Refers to values measured for an undamaged plate
k_{mn}	Stiffness between points m and n	$(\ )_{dmg}$	Refers to values measured for a damaged plate
$\dfrac{\partial H_{pq}}{\partial k_{mn}}$	Partial derivative of H_{pq} with respect to k_{mn}		

1 INTRODUCTION

1.1 Background

Damage prognosis is an estimate of a system's remaining useful life [1]. Because protection of human life and capital assets are paramount concerns for most organizations, many systems are operated on a time-based maintenance or replacement schedule as a protection against equipment failing in service. Damage prognosis provides a means by which a piece of equipment can be used until the end of its useful life, and allow for a potentially money-saving dynamic maintenance schedule. While the definition of 'useful life' will vary from one industry to another, applications that could benefit from damage prognosis include industrial equipment (e.g. heavy mining equipment), explosive containment vessels, and military craft. In the industrial sector, accurate damage prognosis techniques would allow usage fees to be exacted for life used, rather than time used. In the case of military craft, damage prognosis would help the operator to make mission-critical decisions in an effort to increase combat asset readiness.

1.2 Motivation

The wings of unmanned military aircraft are typically constructed of composite material, and during flight and even routine maintenance ("hangar rash"), these wings experience impact loads resulting in uncertain damage to the composite structure. Of particular concern for aircraft operators is local damage that adversely affects a global property, such as a plane's flutter characteristics. Impact damage must fall into three general categories: negligible damage, moderate damage, and catastrophic damage. The first and third categories are not a concern for this study, because the former is defined as such, and the consequences of the latter are obvious. The study of such moderate damage is important because it is uncertain whether a given mission can be completed, or the plane can even be recovered. Of specific interest to this study is damage resulting in delamination of composite plies.

1.3 Purpose

This study attempts to identify particular failure indicators for impact induced composite delamination in an attempt to quantify moderate damage levels, and attempts to apply a reliability-based model to predict a plate's probability of failure. A possible definition of failure is a change in the ultimate strength of a plate, which could be indicated by shifts in certain natural frequencies or changes in stiffness. Studies have demonstrated the ability to determine the location and magnitude of a projectile impact on a composite plate using strain gauges and neural networks trained with numerical simulations [2]. In order to produce an effective damage prognosis, this knowledge must be combined with an appropriate failure model for the system. It was hoped that the results of this study would give researchers a basis on which to build sophisticated models for operational application of damage prognosis to composite structures.

1.4 Roadmap

Section 2 describes the probabilistic method that was originally intended to be applied. Section 3 describes the test structures and experiments performed and presents the experimental results from which the predictive model was developed. Section 4 addresses the finite element model developed and explains how that model was used to guide the experimentation. Section 5 presents the analysis of the results obtained. Section 6 presents the study's conclusions, and sections 7 and 8 provide acknowledgements and references, respectively.

2 Probabilistic Reliability Methods

The original intention of this project had been to perform a reliability analysis for composite plates. This analysis could have been applied or used as a basis for developing a reliability analysis for more complicated composite structures. The basic procedure to developing such an analysis is outlined as follows. The failure modes and the variables which control those modes must be identified. These variables may be random and may have some sort of a distribution. In any case, a distribution must be assumed for each of the influential variables, and these distributions are to be used to create a limit state function for each failure mode. The limit state function is application specific, and defines a boundary between safe operating region and an unsafe region. A joint probability density function of the demand on, and capacity of, a system can be used to represent operating regions of the system (Figure 1), where the safe and unsafe regions are separated by the state at which demand (D) equals capacity (C), such that g=C-D. The probability of a system's failure results from integrating the joint-probability density function across all random variables for the unsafe region of the parameter domain ($g < 0$).

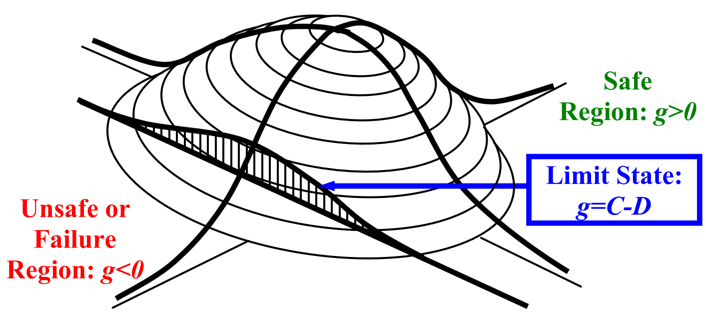

Figure 1. Joint Probability Density Function

Application of this method, however, would require that the variables controlling the defined failure modes have a quantifiable distribution. With such a distribution, probability of failure could be analytically or experimentally determined with reasonable confidence. The failure mode chosen for this study was a drop in the ultimate strength, which might have been predicted by the controlling variables in this study, shifts in natural frequencies. An equation relating shift in frequencies to ultimate strength may have taken the form of US = $C_1\Delta F_1 + C_2\Delta F_2$, where C1 and C2 are constants and ΔF_1 and ΔF_2 are the shifts in the natural frequencies of the first torsional and bending modes. The probability of failure could then be determined by $P_F = \iint_{g<0} g d\Delta F_1 d\Delta F_2$, where g is the failure function, defined by the ultimate strength minus the predicted load. However, an accurate measure of the ultimate strength could not be obtained, and shifts in natural frequency and stiffness were smaller than the unit-to-unit variability. As such, it was not reasonable to apply probabilistic reliability methods to these composite plates. More consistent manufacturing methods and more realistic test boundary conditions may allow such methods to be applicable.

3 Test Structures and Experimentation

The plates, described in section 3.1, were initially characterized in the method described in section 3.2. Section 3.3 depicts the process by which the plates were damaged, after which they underwent a second full modal test, addressed in section 3.4. After collecting all the relevant data, an attempt was made to test the plates to failure in order to determine how their ultimate strength changes with damage level. This process is described in section 3.5.

Table 1: Nominal Composite Material Properties

Property	Symbol	SI Units	English Units
Fiber Volume Fraction	V_f	0.60	0.60
Density	ρ	1.6E +04 kg/m^3	1.5E –04 blobs/in^3
Modulus (with grain)	E_{11}	145 GPa	21000 ksi
Modulus (across grain)	E_{22}	7.93 GPa	1150 ksi
Shear Modulus	G_{12}	5.52 GPa	800 ksi
Poisson's Ratio	ν	0.27	0.27

3.1 Plate Description

The plates measured nominally 152 mm (6 inches) square by 1 mm (0.04 inches) thick. They were constructed of eight 0.127 mm (0.005 inches) thick orthotropic carbon fiber plies in a $[0\ 45\ 90\ {-45}]_S$ layup. The material properties are summarized in Table 1.

3.2 Initial Characterization

A full experimental modal analysis was performed on each plate to obtain an initial modal characterization. Resonant frequencies, damping values, and mode shapes for each plate were determined.

Each plate was supported on a square of foam egg-crate packing material to simulate free-free conditions. The plate was instrumented with seven accelerometers having nominal sensitivities of 10 mV/g and was excited by roving an impact hammer over a grid of 25 points laid out on the plate, as shown in Figure 2.

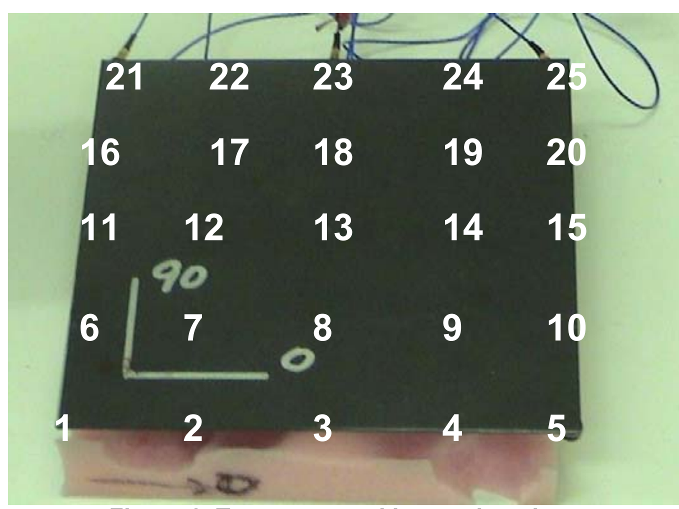

Figure 2. Test setup and impact locations

The data were collected by an eight-channel data acquisition system. A frequency range of zero to one kilohertz was used, with a frequency resolution of 0.625 hertz. Because the response of the plate died out well before the end of the time block, no window was used. Ten averages were taken at each impact location. The data collected were exported as Universal File Format (UFF) files for analysis with third-party experimental modal analysis software.

3.3 Impact Damage

The plates underwent impact damage in an attempt to produce moderate level delamination of the plies. A nominally 31-gram nylon projectile with a 1.27 cm (0.5-inch) diameter and hemispherical head impacted the plates, which were suspended in the test chamber with 22-gauge wire to simulate free-free conditions. The plates were prepared for impact by securing the wire along one edge of the plate with a standard 5-minute epoxy. The plates were carefully positioned in the test chamber, as shown in Figure 3, such that the projectile would impact the center of the same quadrant on each plate, point nine (Figure 2). An FEA model, described in Section 4, was used to determine this location. The projectile was propelled by the force from a pressurized gas chamber, and had velocities varying from 29 m/s to 53 m/s, with most of the projectiles velocities clustering around 50 m/s. The nature of the impact was such that most of the epoxy separated violently from the plate, allowing the freed plate to come to rest on the padding that lined the test chamber. Upon visual inspection, the plates exhibited increasing levels of damage with increasing velocity, ranging from no visual sign of damage to severe delamination and matrix cracking.

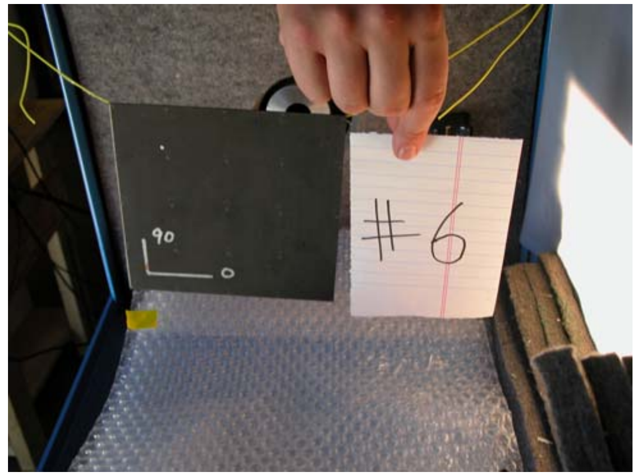

Figure 3. Plate prepared for impact damage

3.4 Damaged Plate Characterization

After the infliction of the impact damage, the plates underwent a second full modal test in order to provide a damaged state modal characterization. The test setup was repeated exactly as in the first modal characterization. Direct comparison of the dynamic properties of the plates before and after the infliction of permanent impact damage was necessary to provide information on which characteristics could be used as damage indicators.

3.5 Ultimate Strength Testing

Ultimate strength testing is typically not an option for damage prognosis, because it destroys the system for which the prognosis is desired. However, in this study it was attempted to measure the ultimate strength of the plates in an MTS machine. Although it had been anticipated that the plates would be tested to failure, they were so flexible that the geometry of the test setup would not allow a great enough displacement to break the plates (Figure 4). A peak value was obtained on a load-displacement curve, but this value is associated with a point where the plate slipped in the MTS machine, and is probably not related to the ultimate strength of the plate. The plates were supported symmetrically by roll bars along either side of the diagonal crossing the damaged region, and pressure was applied along the length of the diagonal by a 1.27 cm (0.5 inch) diameter steel bar. The plates were forced to a deflection of 30 cm at a rate of 10 mm/min. The plates typically regained their shape after removal of the load, though it is expected that there was significant structural damage, because cracking noises were observed as the plates deformed.

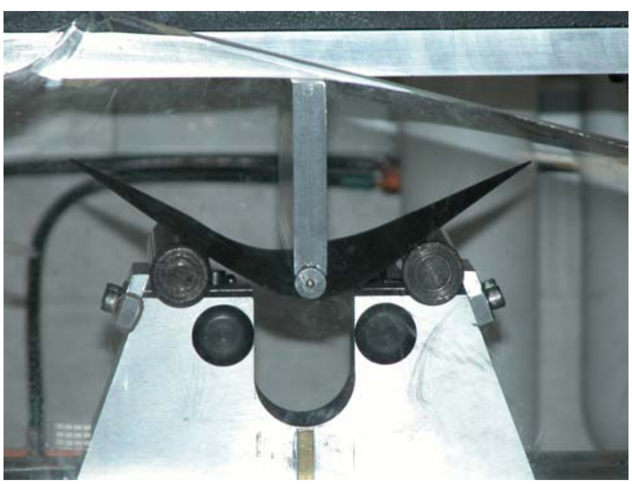

Figure 4. Ultimate Strength Testing

3.6 Test Variations

As can be expected in any experimental process, there were variations from one test to another. Every effort was made to maintain a consistent testing environment. In the modal test, the plates were mounted with the same orientation on the same foam egg-crate packing material for each test, and the accelerometers and wires, which may have slightly altered the boundary conditions, were always mounted in the same direction. A brief study was performed to determine the repeatability of testing: plate 16 was tested at the end of one day, the experimental setup was left overnight in a locked laboratory, and the plate was tested again the following morning. Much care was taken to ensure the repeatability of the experiment, but there was still an average 1% difference in the natural frequencies determined for each test. There was even more variability in the natural frequencies from one plate to another. These results are summarized in Table 3. The wide range of frequencies determined for each mode can be attributed to the unit-to-unit variability in the manufacturing process for the composite plates.

4 FINITE ELEMENT ANALYSIS

4.1 Model Description

A Finite Element Analysis (FEA) model was developed to direct the application of the impact damage to the most effective location. The FEA model was also used to choose candidate features to act as damage indicators in composite plates. The plates were modeled with free-free conditions, consisted of eight layers of three dimensional orthotropic shell elements, and had the material properties presented in Table 1. Each layer was oriented in the same manner as the plate layup, described in section 3.1. Spring elements were used to constrain the plies to one another in the x, y, z, r_x, and r_y degrees of freedom. Because of the small size of the plates, the mass effects of the accelerometers used during testing were included in the model. Each accelerometer comprised 1.2% of the total mass of the system. A MATLAB script was used to generate the input geometry files for the composite plate model, and FEMtools calculated the natural frequencies and mode shapes with a Lanzcos eigenvalue solver.

4.2 Test Analysis Correlation

FEMtools was also used to calculate the Modal Assurance Criterion (MAC) for 13 mode shapes between 100 and 1200 hertz to compare the FEA model mode shapes to the experimentally determined mode shapes. The MAC (Figure 5), showed an average correlation of 92.0%, with the lowest correlation being 81.0 %. Much of this error can be attributed to the limited extent to which the material properties were known, and to the difficulty in replicating the experimental boundary conditions in the model.

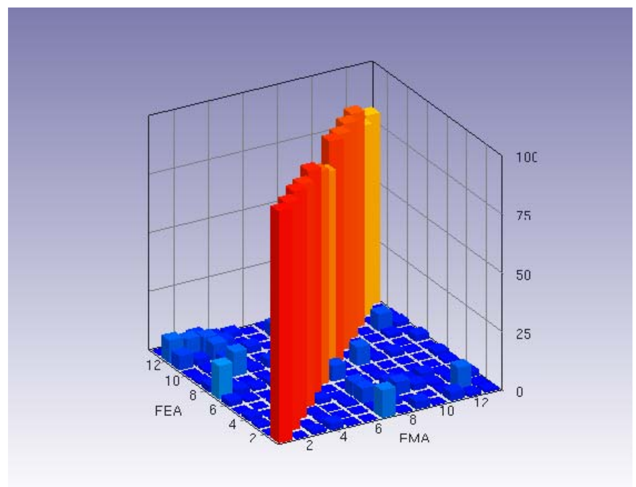

Figure 5. Modal Assurance Criterion

4.3 Impact Location Efficacy Study

The model's ability to predict the behavior of an undamaged plate justified the attempt to use the model to predict the behavior of a damaged plate. Damage in the form of delamination was simulated in the FEA model by decreasing the stiffness of the springs connecting the layers in a local region by several orders of magnitude A brief study was conducted to determine the location for which impact damage would be most effective. The efficacy of an impact location is defined by the amount of global effect induced by a local impact. Damage was simulated for the center, the center of an edge, and the corner of the plate. A review of the resulting changes in natural frequencies and mode shapes revealed that the frequencies were most responsive to damage applied near the plate's corner. Based on these results, it was decided that the projectile would strike at the center of one quadrant, namely, point 9, as shown in Figure 2.

4.4 Impact Damage Simulation

Damage was simulated in the FEA model in an attempt to gain insight into the influence of damage in composite plates. Only the expected damage mechanism, delamination, was simulated in the FEA model. In reality, the plates also experienced matrix cracking of the plies, which severely limited the ability of the FEA model to accurately predict the behavior of the damaged plates. While the FEA model did predict frequency changes with increasing damage that followed some of the same general trends as those in the actual plates, the overall correlation was quite low, as shown by a MAC between the FEA model and a damaged plate (Figure 6). Only three modes correlated better than 80%. The FEA model predicted negligible changes in lower order modes even with severe simulated damage (damage simulation is described in section 3.3). Higher order modes experienced changes in frequencies on the order of 1%.

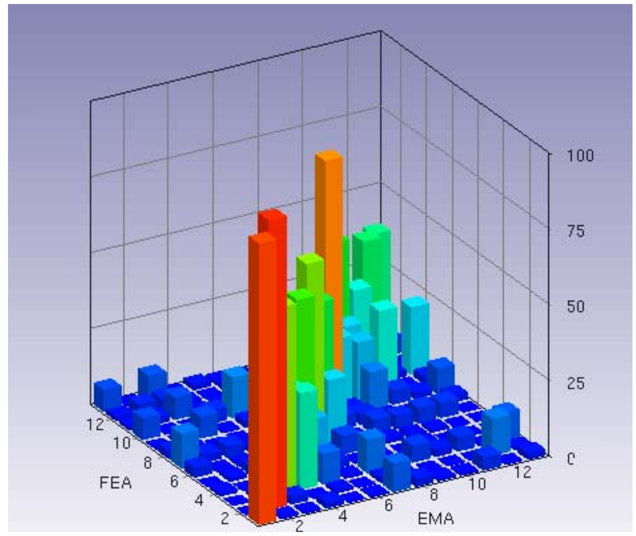

Figure 6. MAC between damaged plate and model

Although the FEA model did not sufficiently model the actual damage introduced into the plates, it did provide one correct, albeit unexpected, prediction about the effects of the damage. In some simulations with significant damage, a higher mode would appear or disappear and an adjacent mode would experience an increase in frequency. Such a result is counterintuitive, because increases in frequency are commonly associated with an increase in stiffness or a decrease in mass, neither of which were expected to occur in the plates. However, this phenomenon was also recorded in the experimental results, although among different modes. While the cause of this increase in natural frequency of some higher order modes is unknown, it is interesting to see that the existence of such unusual results are confirmed by the FEA model, even in light of the gross approximations made in simulating the impact damage.

5 ANALYSIS OF RESULTS

5.1 Data Reduction

The data from the modal tests were analyzed using ME'scope, and natural frequencies, damping values and residues were calculated using a polynomial curve-fitting technique. These data were exported as UFF files, which could be brought into FEMtools for comparison to another test or to the FEA model results. Thirteen modes were identified between 100 and 1100 Hertz both before and after the damage. The results of these calculations are summarized in Table 3, along with the standard deviation and average percent deviation for each natural frequency. Varying less than 2% from one unit to another, the spread seemed very reasonable, but that level of variation was unfortunately greater than the percent change observed after damage in the individual plates' natural frequencies.

Table 3: Experimental Modal Analyses Results

	Undamaged Plate			Damaged Plate			
Mode	Avg. Freq.	Std. Dev.	% Dev.	Avg. Freq.	Std. Dev.	% Dev.	% Diff
1	105.28	3.76	3.57	103.73	4.66	4.49	1.47
2	184.71	2.10	1.13	179.53	3.93	2.19	2.81
3	261.18	5.09	1.95	255.89	6.64	2.59	2.03
4	304.04	7.45	2.45	302.37	7.58	2.51	0.55
5	367.72	5.50	1.50	361.07	8.97	2.48	1.81
6	500.38	6.38	1.27	504.48	23.65	4.69	-0.82
7	518.61	7.97	1.54	526.48	10.70	2.03	-1.52
8	612.45	8.35	1.36	615.33	17.88	2.91	-0.47
9	790.67	18.75	2.37	792.49	14.82	1.87	-0.23
10	883.14	11.85	1.34	873.81	18.61	2.13	1.06
11	930.75	11.11	1.19	918.62	17.24	1.88	1.30
12	973.50	16.42	1.69	963.92	21.80	2.26	0.98
13	1027.4	15.38	1.50	1016.3	10.87	1.07	1.08
Avg.			**1.76**			**2.55**	**1.24**
* % Dev = Standard Deviation/Average Frequency							

5.2 Modal Characterization Analyses

In general, the same 13 natural frequencies were found to correlate before and after the impact damage, with small percent changes in frequency because of the damage. Thirteen MAC matrices were generated comparing all 20 plates among themselves for each mode shape. This comparison was intended to provide information on which modes would be more useful to track in the event of damage; the modes exhibiting the least variation over the 20 plates might also exhibit a more uniform change after the impact damage. In reality, the changes observed after damage were so small that such a knowledge of the consistency of individual mode shapes did not prove to be useful. Table 3 summarizes the results of the unit-to-unit variability and the percent changes after the impact damage. However, in addition to the 13 correlated mode shapes, some plates exhibited new modes in the higher frequency range. In this event, an adjacent mode would experience an increase in natural frequency. Increases in natural frequency are usually associated with an increase in stiffness or a decrease in mass, neither of which occurred in this experiment. However, these results are qualitatively confirmed by the finite element model. Increases in stiffness are represented by a negative sign in Table 3.

5.3 Local Stiffness Effects

Because the impact damage caused such a small change in global properties, an investigation into the effect of the damage on local properties was conducted. It can be shown that, for a lumped-parameter system, $\frac{\partial H_{pq}}{\partial k_{mn}} = (H_{pm} - H_{pn})(H_{qm} - H_{qn})$, where H is the frequency response function and k is the stiffness between two points. This expression can be converted into a useful approximation for local stiffness changes by replacing ∂ with Δ and doing some algebraic manipulation.

$$\partial H_{pq} \approx \Delta H_{pq} = (H_{pq})_{und} - (H_{pq})_{dmg}, \quad \text{therefore,} \quad \Delta k_{mn} = \frac{(H_{pq})_{und} - (H_{pq})_{dmg}}{\left[(H_{pm})_{und} - (H_{pn})_{und}\right]\left[(H_{qm})_{und} - (H_{qn})_{und}\right]}.$$

This equation should yield the change in local stiffness caused by the damage. However, the equation is derived for a lumped mass system; therefore, care must be taken in using it to approximate a continuous system, such as a plate. While the preferred goal of this study would be to measure changes in global properties, it seemed reasonable to expect that properties near the impact would be more affected by the damage, and therefore differences in properties, such as stiffness, would be easier to measure. The results of this investigation are shown in Figure 7, which shows how the change in stiffness generally increases with the velocity of the projectile. However, this data is not strong enough to base any concrete scientific conclusions on. While most of the plates experienced damage in the same manner, four plates, possibly because of variations in the manufacturing process or variations in the impact damage process, exhibited significantly different damage mechanisms than the rest of the group. These data points are shown with red X's in Figure 7. Two additional plates were excluded completely because their impact velocities were unknown. While removal of these aberrant plates resulted in the generally expected trend, such methods cannot be used to produce conclusive quantitative results.

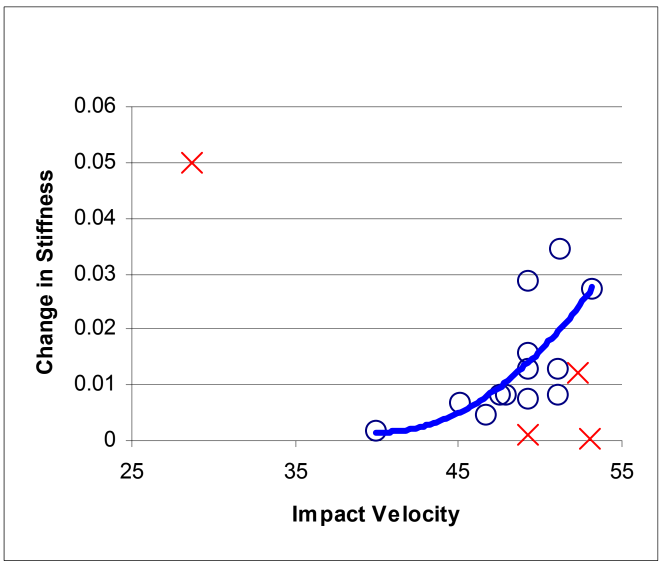

Figure 7. Change in Stiffness vs. Velocity

5.4 Ultimate Strength versus Frequency Shift

Determination of natural frequencies is a convenient form of non-destructive testing, and the coupling of the first torsional and first bending modes of an airplane wing has a strong influence on the flutter characteristics of the airplane. In researching failure prediction of composite plates, a matter of high importance was tracking shifts in the frequencies of these modes. The expectation had been that a linear or quadratic formula could be written to fit the relationship between the shift of one or more frequencies and the ultimate strength. The average frequency shift for the 13 modes recorded was 1.2 %. Because such a small shift in natural frequencies was observed, and because an adequate measure of the ultimate strength could not be obtained, it would be ineffective to relate the shifts to the plate's ultimate strength. While it may be the case that, in a batch of plates with zero variability, frequency shifts could accurately predict changes in ultimate strengths, such a situation is not practical in the laboratory, and certainly not with operational aircraft wings.

6 CONCLUSION

The original goal of the experiment had been to apply reliability methods in an attempt to predict failure probability in composite plates. While failure criteria vary from one application to another, the definition of failure anticipated for a composite plate was an arbitrary decrease in the ultimate strength of the plate. The variables chosen that could control this failure mode were the natural frequencies of the plate, because of the lower modes' inherent importance in determining the flutter properties of an airplane. Unfortunately, there were several reasons why this approach did not prove to be helpful. Because of their flexibility, the plates did not break in the ultimate strength testing phase, and the primary failure mode could not be measured. Without an actual measure of the ultimate strength, it would have been impossible to fit a model mapping shifts in natural frequencies to a decrease in ultimate strength. However, the shifts in natural frequencies that were measured were not useful, because the unit-to-unit variability overwhelmed the percent changes observed after damage. These problems may have been avoided by conducting experiments on a plate with more realistic geometry. For example, a thicker plate may have broken in the ultimate strength test. In the case of an aircraft wing, the flutter properties are determined by a coupling between the first torsional and first bending modes. Free-free boundary conditions do not exhibit this coupling effect; geometries with other boundary conditions that would exhibit this coupling effect might provide more useful results. Although these experiments did not produce the desired or expected results, experimentation with more realistic conditions may provide valuable information about the behavior of composite structures.

7 ACKNOWLEDGEMENTS

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